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Apisilviculture: A Profitable Agroforestry System for Sustainable Food Production, Pollinator Conservation and Enhanced Ecosystem Services

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Apisilviculture, the integration of beekeeping with forestry, agroforestry and agricultural systems, has emerged as an important nature-based strategy for addressing food insecurity, pollinator decline, biodiversity loss and climate change. The present review critically examines the ecological, economic and environmental

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significance of apisilvicultural systems in promoting sustainable food production, pollinator conservation and enhanced ecosystem services. A systematic review approach was followed using scientific literature retrieved from major international databases and reports published during 1990–2026, with emphasis on recent advancements from 2015–2026. The review revealed that apisilvicultural systems significantly improve pollination services, crop productivity, biodiversity conservation and ecological resilience through integration of flowering trees, shrubs, crops and pollinators within multifunctional agroforestry landscapes. Pollinator-dependent crops such as mango, citrus, cucurbits, sunflower, coffee and mustard exhibited substantial improvement in fruit set, seed development, yield and quality under pollinator-rich systems. Multipurpose tree species including *Azadirachta indica*, *Eucalyptus* spp., *Acacia nilotica*, *Pongamia pinnata*, *Syzygium cumini* and *Moringa oleifera* were identified as important nectar and pollen resources supporting pollinator populations throughout the year. The review further demonstrated that apisilviculture enhances ecosystem services such as carbon sequestration, nutrient cycling, soil conservation, watershed protection and climate resilience. Economically, these systems generate diversified outputs including honey, beeswax, fruits, timber, fodder and intercrop yields while improving agricultural productivity through pollination services. However, climate change, habitat degradation, pesticide exposure and floral scarcity remain major threats affecting pollinator sustainability. Overall, the review established that apisilviculture is a profitable, climate-smart and ecologically sustainable agroforestry practice capable of simultaneously supporting food security, pollinator conservation and ecosystem restoration. Promotion of integrated tree–crop–bee systems and pollinator-friendly landscapes is therefore essential for sustainable agricultural development and long-term ecological resilience.

Keywords: Apisilviculture; apiculture; pollinator conservation; sustainable food production; agroforestry systems; ecosystem services; pollination services; biodiversity conservation; bee forage trees & crops.

1. Introduction

The sustainability of global food production systems is increasingly threatened by climate change, biodiversity loss, pollinator decline, land degradation and unsustainable agricultural intensification. Rapid urbanization, deforestation, habitat fragmentation and excessive dependence on chemically intensive monoculture agriculture have severely disrupted ecological processes that regulate agricultural productivity, ecosystem stability and environmental resilience. Among these emerging challenges, pollinator decline has become one of the most serious ecological concerns of the twenty-first century because pollinators are indispensable for crop production, forest regeneration and maintenance of terrestrial biodiversity (IPBES, 2016; Potts et al., 2016). Pollinators contribute directly or indirectly to the reproduction of nearly 75% of globally important food crops and approximately 87–90% of flowering wild plant species, thereby sustaining food systems and ecosystem functioning worldwide (IPBES, 2016; Potts et al., 2016). The global economic value of animal-mediated pollination has been estimated at nearly US$235–577 billion annually, reflecting its enormous contribution to agricultural economies, nutritional security and human well-being (Potts et al., 2016).

Insects, particularly bees, constitute the most efficient and economically important pollinators in terrestrial ecosystems. Honey bees (*Apis mellifera* and *Apis cerana*), solitary bees, bumble bees, butterflies, moths, hoverflies and beetles collectively support pollination services in both cultivated and natural ecosystems. Pollinator diversity not only enhances crop yield but also improves yield stability, fruit quality and ecosystem resilience under varying environmental conditions (Katumo et al., 2022). Pollinator-dependent crops are major sources of essential vitamins, minerals, lipids and micronutrients required for balanced human nutrition. Studies have demonstrated that crops dependent upon pollination contribute significantly to global supplies of vitamin C, vitamin A, folate and several antioxidant compounds essential for human health and nutritional security (Smith et al., 2015; Chaplin-Kramer et al., 2014).

Despite their immense ecological and economic significance, pollinator populations are declining globally at alarming rates. Habitat destruction, indiscriminate pesticide use, invasive pests and pathogens, environmental pollution, land-use change and climate change are major drivers responsible for widespread pollinator decline (Potts et al., 2010; Greenleaf et al., 2007). Agricultural intensification and habitat simplification through monoculture farming systems have drastically reduced floral diversity and continuity of nectar and pollen resources, thereby weakening pollinator populations and destabilizing pollination services. Long-term ecological studies in Europe and North America have documented substantial reductions in insect biomass and pollinator richness over recent decades (Hallmann et al., 2017; Powney et al., 2019). Climate change further intensifies these threats by altering flowering phenology, pollinator distribution and plant–pollinator synchrony, consequently affecting ecological stability and agricultural productivity.

The consequences of pollinator decline extend far beyond reduced agricultural productivity. Pollinators are integral components of ecosystem functioning because they facilitate sexual reproduction, genetic exchange and regeneration of flowering plants. Decline in pollination services therefore threatens biodiversity conservation, forest regeneration and ecological resilience. Recent modelling studies suggest that severe pollinator decline may negatively affect global food supply, nutritional security and rural economies, particularly in developing countries where pollinator-dependent agriculture supports millions of smallholder farmers and forest-dependent communities (Aizen et al., 2009; Bauer and Wing, 2016). Loss of pollinator diversity may also destabilize ecological networks and impair long-term sustainability of terrestrial ecosystems.

Under such circumstances, ecologically sustainable and economically viable land-use systems capable of simultaneously supporting food production, pollinator conservation and ecosystem services are urgently required. Apisilviculture, the deliberate integration of beekeeping with forestry, agroforestry and agricultural systems, has emerged as a promising nature-based solution to these interconnected global challenges. The term combines *Apis* (bee) and silviculture, reflecting the scientific integration of pollinator management within tree-based production systems. Unlike conventional monoculture agriculture, apisilvicultural systems create structurally diverse and ecologically heterogeneous landscapes composed of flowering trees, shrubs, crops and natural vegetation that provide continuous forage resources, nesting habitats and ecological refugia for pollinators throughout the year.

Trees constitute the ecological backbone of apisilvicultural systems because they supply nectar, pollen, propolis, shelter and favorable microclimatic conditions essential for pollinator survival and colony development. Multipurpose tree species such as *Azadirachta indica*, *Albizia lebbeck*, *Pongamia pinnata*, *Dalbergia sissoo*, *Acacia nilotica*, *Syzygium cumini*, *Eucalyptus* spp, *Moringa oleifera* and several horticultural species play critical roles in sustaining bee populations and maintaining floral continuity within tropical and subtropical ecosystems (Mahapatra et al., 2025a; Mahapatra et al., 2025b). Integration of these species within agroforestry systems significantly enhances pollinator abundance, crop pollination efficiency and ecological stability (Bhol et al., 2025). Recent global reviews further demonstrated that agroforestry systems generally maintain or improve pollination services compared with conventional agricultural systems because of enhanced floral diversity, habitat heterogeneity and ecological connectivity (Centeno-Alvarado et al., 2023).

Apisilviculture is increasingly recognized not only as an ecologically sustainable approach but also as a profitable livelihood strategy capable of generating multiple economic outputs. Such systems produce honey, beeswax, pollen, propolis, royal jelly, timber, fuelwood, fodder, fruits and intercrop yields while simultaneously improving crop productivity through pollination services. Importantly, the indirect economic benefits derived from pollination often exceed the direct value of hive products because pollinator activity substantially enhances crop yield, fruit quality and market value. Consequently, apisilviculture offers considerable livelihood opportunities for smallholder farmers, tribal communities and forest-dependent populations while strengthening economic resilience and climate adaptability.

Beyond economic profitability, apisilviculture contributes substantially to enhancement of ecosystem services including biodiversity conservation, carbon sequestration, nutrient cycling, soil stabilization, watershed protection and climate regulation. Pollinator-friendly tree-based landscapes improve ecological connectivity and facilitate movement of pollinators across fragmented habitats. Such systems also moderate microclimatic extremes, improve soil moisture retention and reduce ecological vulnerability under changing climatic conditions. Therefore, apisilviculture is increasingly being promoted as a climate-smart and nature-based strategy for sustainable land management, ecological restoration and resilient food production systems.

Although considerable research has been conducted separately on pollinator ecology, beekeeping and agroforestry systems, comprehensive synthesis of the ecological, economic and environmental dimensions of apisilviculture remains limited. Therefore, the present review critically examines the role of apisilviculture as a profitable agroforestry system for sustainable food production, pollinator conservation and enhanced ecosystem services. The review further highlights recent global developments, ecological significance, economic opportunities, ecosystem functions, prevailing constraints and future research priorities associated with apisilvicultural systems under changing climatic and socio-ecological scenarios.

This manuscript is very important for the scientific community. It provides a comprehensive understanding of apisilviculture as a sustainable tree–crop–bee production system that supports food security, pollinator conservation and ecosystem sustainability. By integrating knowledge from agroforestry, apiculture and pollination ecology, it highlights the ecological and economic potential of apisilviculture as a climate-smart and nature-based solution. The manuscript also identifies future research and policy priorities, making it valuable for researchers, foresters, agroforestry scientists, ecologists and policymakers working towards sustainable land-use systems and biodiversity conservation.

2. Methodology

2.1 Review Framework

The present review on "Apisilviculture: A profitable practice for sustainable food production, pollinator conservation and enhanced ecosystem services" was conducted following a systematic and integrative review approach to synthesize available scientific information related to apisilviculture, pollinator ecology, agroforestry, beekeeping, ecosystem services and sustainable food production. The review aimed to critically evaluate global research trends, ecological functions, economic significance and environmental implications of apisilvicultural systems under changing climatic scenarios.

2.2 Literature Search Strategy

An extensive literature survey was carried out using internationally recognized scientific databases and search engines, including: Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink, PubMed ResearchGate, CAB Direct and FAO IPBES. Also important books, journals and other authentic literature were referred. The literature search primarily covered publications from 1990 to 2026, with greater emphasis on recent studies published during 2015–2026 to capture current advancements in pollinator conservation, agroforestry and ecosystem service research. The following combinations of keywords and Boolean operators were used during literature retrieval: Apisilviculture, Bee forestry, Pollinator conservation, Agroforestry and pollination, Honey bees in agroforestry, Forest-based beekeeping, Pollination ecosystem services, Bee forage trees, Bee forage crops, Sustainable food production, Pollinators and climate change, Agroforestry ecosystem services, Nature-based solutions and pollinators. Honey bee biodiversity, Pollination and crop productivity, and Tree-based pollinator systems.

2.3 Inclusion and Exclusion Criteria

2.3.1 Inclusion Criteria

The review included: Peer-reviewed research articles, Review papers and meta-analyses, Books and book chapters, Conference proceedings of scientific relevance, FAO, IPBES and governmental technical reports and Publications related to: pollinator ecology, agroforestry, forestry, beekeeping, ecosystem services, climate resilience, biodiversity conservation and sustainable agriculture. Priority was given to studies presenting quantitative or qualitative evidence on: pollination services, bee forage resources, agroforestry–pollinator interactions, ecosystem service enhancement, crop productivity, biodiversity conservation and economic profitability of bee-based systems.

2.3.2 Exclusion Criteria

The following were excluded: Non-scientific publications, Duplicated records, Unverified online sources, Studies lacking methodological clarity, Articles unrelated to pollinators, forestry or agroforestry systems, and Publications without accessible abstracts or full texts.

2.4 Screening and Selection of Literature

Initially, all retrieved publications were screened based on title relevance, keywords and abstracts. Subsequently, full-text articles were critically evaluated for scientific quality, relevance and thematic suitability.

The screening process involved: Identification of records through database searching, Removal of duplicate records, Abstract screening for thematic relevance, Full-text evaluation for inclusion and Final selection of eligible studies for synthesis. Special emphasis was given to recent studies addressing: climate-smart pollinator systems, ecosystem service valuation, pollinator decline, agroforestry-based pollination, sustainable beekeeping and multifunctional landscape management.

2.5 Limitations of the Review

Although extensive literature was reviewed, some regional studies and non-English publications may not have been accessible. Variations in methodologies, ecosystem types, pollinator species and agroforestry practices among different studies may also influence direct comparability of results. Nevertheless, the present review provides a comprehensive synthesis of current global knowledge on apisilviculture and its role in sustainable food production, pollinator conservation and ecosystem service enhancement.

3. Results and Discussion

3.1 Concept of Apisilviculture

Apisilviculture is an integrated and multifunctional land-use system that combines beekeeping (apiculture) with silviculture and agroforestry practices to enhance pollination services, biodiversity conservation, ecosystem stability and rural livelihoods (Potts et al., 2010; Garibaldi et al., 2013; Centeno-Alvarado et al., 2023) (Fig. 1). The term originates from the Latin word *Apis* meaning honey bee and *silviculture* referring to the art and science of cultivating forest crops. Thus, apisilviculture refers to the deliberate establishment and management of bee-friendly trees, flowering crops and forest vegetation to support honey bees and other pollinators while simultaneously improving ecological sustainability and economic productivity (Aizen et al., 2009; FAO, 2018).

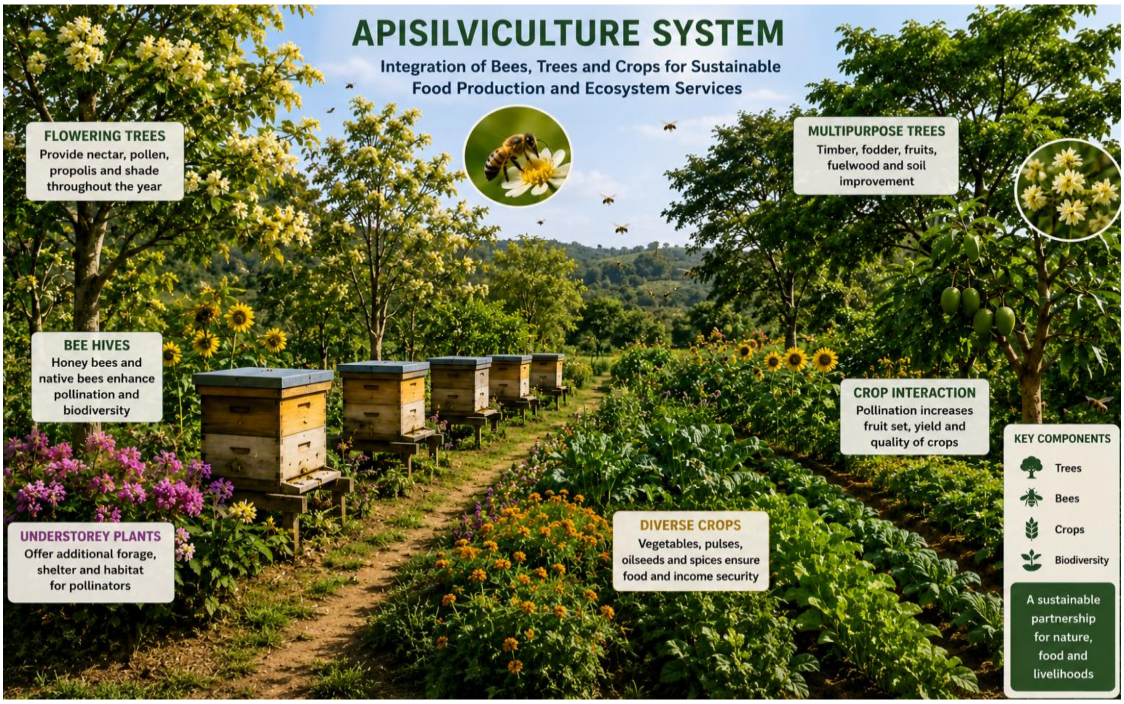

Fig. 1. Pictorial view of an apisilviculture system

The concept of apisilviculture is fundamentally based on the ecological interdependence between flowering plants and pollinators. Forest trees and flowering vegetation provide nectar, pollen, resin and nesting habitats for bees and other pollinating organisms, whereas pollinators facilitate fertilization, seed formation, genetic exchange and regeneration of flowering plant species (Klein et al., 2006; Potts et al., 2016). This mutualistic interaction forms one of the most important ecological foundations of sustainable forest and agricultural ecosystems. Pollinators are known to contribute to the reproduction of nearly 75% of major global food crops and approximately 87–90% of flowering wild plant species (IPBES, 2016; Potts et al., 2016). Consequently, pollinator conservation has become an important component of sustainable forestry and agroecosystem management (Garibaldi et al., 2013; Katumo et al., 2022).

Traditionally, forests have served as natural habitats for wild honey bees and sources of honey collection by indigenous communities. However, modern apisilviculture extends beyond traditional honey harvesting and involves scientific integration of beekeeping with tree-based production systems (FAO, 2021). In these systems, nectar- and pollen-rich trees, shrubs, intercrops and flowering herbs are deliberately incorporated into agricultural and forest landscapes to ensure continuous forage availability for pollinators throughout the year (Centeno-Alvarado et al., 2023; Paudel et al., 2025). Such systems are increasingly recognized as nature-based and climate-smart approaches capable of supporting food production, pollinator conservation and ecosystem restoration simultaneously (Potts et al., 2016; Smith et al., 2021).

Unlike conventional monoculture agriculture, apisilvicultural systems create structurally diverse and ecologically heterogeneous landscapes characterized by multilayered vegetation, floral continuity and enhanced habitat connectivity (Jose, 2009; Centeno-Alvarado et al., 2023). Habitat heterogeneity is known to improve pollinator abundance, diversity and ecosystem resilience because different pollinator groups require varied floral and nesting resources (Kennedy et al., 2013; Dainese et al., 2019). Agroforestry landscapes enriched with flowering trees and shrubs therefore function as ecological refugia for both managed honey bees and wild pollinators (Kremen and Miles, 2012; Katumo et al., 2022).

Trees constitute the ecological backbone of apisilvicultural systems because they provide nectar, pollen, propolis, shade, shelter and suitable microclimatic conditions for pollinators (Ricketts et al., 2008; Vanbergen and Initiative, 2013). Multipurpose species such as *Azadirachta indica*, *Albizia lebbeck*, *Acacia nilotica*, *Dalbergia sissoo*, *Pongamia pinnata*, *Leucaena leucocephala*, *Moringa oleifera*, *Syzygium cumini* and several fruit trees are widely recognized as important bee forage resources in tropical and subtropical regions (Crane, 1990; Free, 1993). These species improve floral continuity during lean seasons and enhance pollinator survival under stressful environmental conditions (Nair, 1993; Klein et al., 2006).

The concept of apisilviculture also integrates ecological principles of sustainable land management and ecosystem services. Pollinator-friendly tree-based systems enhance carbon sequestration, nutrient cycling, watershed protection, biodiversity conservation and climate regulation while simultaneously supporting agricultural productivity (Jose, 2009; Power, 2010). Agroforestry systems are increasingly recognized as biodiversity-rich landscapes capable of restoring ecological functions degraded by intensive agriculture (Tscharntke et al., 2012; Dainese et al., 2019). Recent studies further demonstrated that diversified agroforestry systems generally maintain higher pollinator abundance and pollination services compared with simplified monoculture systems (Centeno-Alvarado et al., 2023; Paudel et al., 2025).

Economically, apisilviculture is considered a highly profitable and resilient production system because it generates diversified outputs including honey, beeswax, pollen, propolis, royal jelly, fruits, timber, fuelwood, fodder and intercrop yields (Bradbear, 2009; FAO, 2021). Pollination services provided by bees often contribute greater economic value than direct hive products because improved pollination significantly enhances crop yield, fruit quality and seed production (Garibaldi et al., 2013; Bauer and Wing, 2016). Consequently, apisilviculture provides substantial livelihood opportunities for smallholder farmers, tribal communities and forest-dependent populations, particularly in tropical developing countries where ecosystem services remain central to rural economies (Aizen et al., 2009; Smith et al., 2015).

The review of literature further indicates that apisilviculture contributes significantly to conservation of pollinator diversity and restoration of degraded landscapes (Potts et al., 2010; Vanbergen and Initiative, 2013). Pollinator-friendly landscapes improve ecological connectivity and facilitate movement of pollinators across fragmented habitats, thereby strengthening plant–pollinator interactions and ecosystem resilience (Kennedy et al., 2013; Dainese et al., 2019). Such systems also moderate microclimatic extremes, improve soil moisture retention and increase adaptability under changing climatic conditions (Jose, 2009; Potts et al., 2016).

3.2 Foraging Range of Honey Bees

The review of literature revealed substantial variation in the foraging range of honey bees and other pollinators depending upon species characteristics, floral resource availability, habitat structure and climatic conditions

(Table 1). Among the different pollinators, *Apis mellifera* exhibited the widest and most flexible foraging range, generally covering 1–3 km from the hive under normal environmental conditions, although flights exceeding 10 km were occasionally recorded under forage scarcity (Beekman and Ratnieks, 2000; Couvillon et al., 2014). Such extensive foraging ability enables *A. mellifera* colonies to exploit dispersed floral resources efficiently across heterogeneous landscapes, making them highly valuable for large-scale agricultural pollination and commercial apiculture.

The review further indicated that *Apis cerana indica*, the indigenous Asian honey bee, generally forages over comparatively shorter distances ranging between 0.5 and 2 km. However, this species demonstrates greater adaptability to tropical forests, hilly terrains and fragmented agroforestry landscapes than *A. mellifera* (Oldroyd and Nanork, 2009). Its efficient foraging behaviour under humid tropical conditions makes it highly suitable for apisilvicultural systems in South and Southeast Asia.

Wild honey bees such as *Apis dorsata* exhibited remarkably long foraging ranges associated with migratory behaviour and dependence on mass flowering forest trees (Punchihewa et al., 1985). Such species play crucial ecological roles in forest pollination and maintenance of biodiversity because they facilitate long-distance pollen transfer and genetic exchange among plant populations. Conversely, smaller bee species such as *Apis florea* and stingless bees generally displayed shorter foraging ranges because of smaller body size and lower flight capacity (Greenleaf and Kremen, 2006). Nevertheless, these pollinators contribute significantly to localized pollination services within agroforestry systems and natural ecosystems.

The table also demonstrates that body size strongly influences pollinator foraging distance. Greenleaf and Kremen (2006) observed a positive relationship between bee body size and maximum foraging range across different bee taxa. Larger bees such as bumble bees and *A. dorsata* are capable of traveling longer distances, whereas solitary bees and stingless bees remain relatively localized around nesting habitats. Gathmann and Tscharntke (2002) similarly reported that many solitary bees forage within only a few hundred meters from their nests, highlighting the importance of maintaining floral resources close to nesting sites.

Landscape structure and habitat heterogeneity were identified as major determinants of pollinator movement and foraging efficiency. Diverse agroforestry systems containing flowering trees, shrubs, intercrops and natural vegetation support shorter and more energetically efficient foraging trips because floral resources are continuously available within accessible distances (Steffan-Dewenter and Kuhn, 2003). In contrast, simplified monoculture landscapes often compel bees to travel longer distances due to seasonal scarcity of nectar and pollen resources (Kennedy et al., 2013). Such long-distance foraging increases energy expenditure and may negatively affect colony productivity and pollination efficiency.

Tree-based apisilvicultural systems significantly improve pollinator foraging conditions by ensuring year-round floral continuity. Flowering tree species such as *Eucalyptus* spp., *Azadirachta indica*, *Albizia lebbeck*, *Syzygium cumini*, *Acacia nilotica* and *Pongamia pinnata* provide abundant nectar and pollen resources during different seasons, thereby reducing forage scarcity and supporting colony health (Crane, 1990; Bradbear, 2009). Such systems also improve ecological connectivity among floral patches and facilitate pollinator movement across fragmented habitats.

The review further highlighted that pollinator diversity contributes substantially to ecosystem resilience and crop productivity. Although managed honey bees are major commercial pollinators, wild pollinators including solitary bees, stingless bees, hoverflies and bumble bees provide complementary pollination services and improve overall pollination stability (Garibaldi et al., 2013). Therefore, conservation of diverse pollinator communities within apisilvicultural landscapes is essential for sustainable food production and ecosystem functioning.

Climate change and anthropogenic disturbances are increasingly affecting pollinator foraging behaviour and movement patterns. Rising temperatures, habitat fragmentation, pesticide exposure and altered flowering phenology may disrupt plant–pollinator synchronization and reduce foraging efficiency (Potts et al., 2010; Goulson et al., 2015). Under such circumstances, diversified agroforestry and apisilvicultural systems can function as ecological refugia by providing stable floral resources and favorable microclimatic conditions for pollinators.

3.3 Potential Forage Trees and Shrubs for Profitable Apisilviculture

The Table 2 clearly demonstrates that profitable apisilviculture depends upon integration of diverse forestry, agroforestry, horticultural and ornamental species capable of supplying nectar and pollen resources throughout the year. The inclusion of horticultural trees and shrubs significantly enhances the ecological and economic sustainability of apisilvicultural systems because fruit crops and plantation species not only support pollinator nutrition but also directly benefit from insect-mediated pollination through improved fruit set, yield and quality (Klein et al., 2006; Garibaldi et al., 2013).

The review indicated that horticultural fruit trees such as mango, citrus, litchi, guava, jamun and papaya are highly important components of pollinator-friendly agroecosystems. These species produce abundant nectar and pollen during flowering and attract diverse pollinator assemblages including honey bees, solitary bees and hoverflies. Pollination by bees substantially improves fruit set, fruit size, seed formation and market quality in these crops (Abrol, 2012; Klein et al., 2006). Consequently, integration of horticultural crops within apisilvicultural systems generates dual economic benefits through fruit production and enhanced honey yield.

Plantation crops such as coffee, tea, coconut and arecanut also emerged as important pollinator-supporting species. Coffee agroforestry systems containing shade trees and flowering understory vegetation support high pollinator diversity and improve coffee yield and quality through effective pollination services (Schroth et al., 2004). Similarly, coconut and arecanut plantations provide continuous floral resources under tropical conditions, thereby supporting year-round pollinator activity.

The review further revealed that ornamental shrubs and medicinal plants contribute substantially to floral continuity within apisilvicultural landscapes. Species such as rose, hibiscus, bougainvillea, henna and *Vitex negundo* provide nectar during periods of limited flowering in major crops and trees. Integration of ornamental and medicinal shrubs along farm boundaries, home gardens and hedgerows therefore improves habitat heterogeneity and pollinator abundance.

Forestry and agroforestry species remain ecologically indispensable because of their long flowering duration, habitat support and ecosystem service functions (Mahapatra et al. 2025a & Bhol et al., 2025). Nitrogen-fixing trees such as *Acacia nilotica*, *Albizia lebbeck*, *Leucaena leucocephala* and *Gliricidia sepium* improve soil fertility while simultaneously supporting pollinator diversity. Drought-tolerant species such as neem and ber provide floral resources during dry seasons and thus improve resilience of pollinator populations under climatic stress conditions.

The Table also highlights the importance of staggered flowering phenology in sustaining profitable apisilviculture. Species exhibiting multiple flowering flushes or year-round blooming behaviour such as *Moringa oleifera*, hibiscus and subabul are especially valuable because they minimize seasonal forage scarcity. Sequential flowering among trees, shrubs and horticultural crops ensures continuous nectar and pollen availability, thereby maintaining colony strength and honey production throughout the year.

The review further confirmed that diversified apisilvicultural systems support higher pollinator richness and ecosystem stability than simplified monoculture systems (Kennedy et al., 2013; Centeno-Alvarado et al., 2023). Landscapes enriched with flowering trees, shrubs and fruit crops improve ecological connectivity, reduce pollinator stress and enhance ecosystem services including pollination, carbon sequestration, soil conservation and biodiversity conservation.

From an economic perspective, inclusion of horticultural trees and shrubs greatly improves profitability because pollinator-dependent fruit crops generate high market value while simultaneously enhancing honey production. Therefore, integrated tree–crop–bee systems involving forestry species, horticultural crops and flowering shrubs represent highly sustainable and profitable models for climate-resilient agriculture and rural livelihoods.

3.4 Potential Vegetable, Pulse, Oilseed and Cereal Crops Suitable for Profitable Apisilviculture

The review of literature clearly indicated that integration of agricultural crops with forestry and agroforestry species substantially improves the profitability and ecological sustainability of apisilvicultural systems (Table 3). Vegetable, pulse, oilseed and cereal crops function not only as food and income sources but also as important providers of nectar and pollen resources for honey bees and other pollinators. Inclusion of such crops within tree-based systems ensures seasonal continuity of floral resources, enhances pollinator abundance and improves crop productivity through effective pollination services.

Table 1. Fogaring range of honey bees

Bee species/ Pollinator	Average foraging range	Maximum recorded range	Major influencing factors	Ecological significance	Key references
Apis mellifera	1–3 km	10–12 km	Floral abundance, colony strength, landscape structure, season	Major commercial pollinator with extensive landscape coverage	Visscher and Seeley (1982); Beekman and Ratnieks (2000); Couvillon et al. (2014)
Apis cerana indica	0.5–2.0 km	4–6 km	Forest vegetation, local climate, floral continuity	Efficient pollinator in tropical and fragmented landscapes	Oldroyd and Nanork (2009); Partap (2011)
Apis dorsata	2–5 km	>10 km	Availability of mass flowering trees, migration behaviour	Important wild pollinator of forest ecosystems	Crane (1990); Punchihewa et al. (1985)
Apis florea	0.2–1.0 km	2–3 km	Small colony size, shrub vegetation, climatic conditions	Pollination in dryland and semi-arid ecosystems	Free (1993); Abrol (2012)
Stingless bees (*Trigona* spp.)	100–800 m	1–2 km	Body size, floral density, habitat complexity	Effective pollinators in localized agroforestry systems	Greenleaf and Kremen (2006); Slaa et al. (2006)
Bumble bees (*Bombus* spp.)	0.5–2.5 km	5 km	Temperature, floral quality, colony size	Highly efficient pollinators under temperate conditions	Osborne et al. (1999); Greenleaf and Kremen (2006)
Solitary bees	150–600 m	1–1.5 km	Nesting habitat, floral resources, body size	Important specialized crop pollinators	Gathmann and Tscharntke (2002); Zurbuchen et al. (2010)
Hoverflies	100–1000 m	2 km	Landscape diversity, nectar resources	Supplementary pollinators and biological control agents	Rader et al. (2016); Kleijn et al. (2015)

Table 2. Potential forestry, horticultural trees and shrubs suitable for profitable apisilviculture systems

Species	Category	Major bee resource	Flowering season	Major ecological/ economic importance	Suitable ecosystem/region	Key references
Azadirachta indica (Neem)	Forestry tree	Nectar and pollen	March–May	Medicinal tree, drought tolerant, summer forage	Tropical and semi-arid regions	Crane (1990); Abrol (2012)
Acacia nilotica (Babul)	Forestry tree	Nectar and pollen	June–September	Nitrogen fixation, fodder and gum production	Drylands and agroforestry systems	Nair (1993); Jose (2009)
Albizia lebbeck (Siris)	Forestry tree	Nectar and pollen	April–July	Fast-growing multipurpose tree	Tropical forestry systems	FAO (2018); Crane (1990)
Dalbergia sissoo (Shisham)	Forestry tree	Nectar and pollen	February–April	Timber and nitrogen-fixing tree	Riverine and agroforestry systems	Jose (2009); Nair (1993)

Species	**Category**	**Major bee resource**	**Flowering season**	**Major ecological/ economic importance**	**Suitable ecosystem/region**	**Key references**
Pongamia pinnata (Karanj)	Forestry tree	Nectar	March–May	Biofuel tree and bee forage	Coastal and tropical dry regions	Abrol (2012); Jose (2009); Mahapatra et al. (2025a)
Leucaena leucocephala (Subabul)	Agroforestry tree	Nectar and pollen	Multiple flushes	Fodder, nitrogen fixation and fuelwood	Agroforestry systems	Nair (1993); FAO (2021)
Gliricidia sepium	Agroforestry tree	Nectar	Seasonal	Green manure and live fencing	Hedgerow agroforestry systems	Jose (2009); FAO (2018)
Calliandra calothyrsus	Shrub/tree	Nectar	Extended flowering	Excellent bee forage and fodder	Tropical hill agroforestry systems	Partap (2011); FAO (2021)
Eucalyptus spp.	Plantation forestry tree	Nectar	Species-specific seasonal flowering	Commercial honey production	Plantation forestry systems	Crane (1990); Bradbear (2009)
Grevillea robusta (Silver oak)	Agroforestry tree	Nectar	March–May	Shade tree and pollinator resource	Coffee agroforestry systems	Schroth et al. (2004)
Moringa oleifera (Drumstick)	Horticultural tree	Nectar and pollen	Nearly year-round	Nutritional, medicinal and bee forage value	Tropical home gardens	FAO (2021); Partap (2011); Mahapatra et al. (2025a)
Mangifera indica (Mango)	Fruit tree	Nectar and pollen	January–March	Pollinator-dependent fruit crop	Tropical orchards	Klein et al. (2006); Abrol (2012)
Syzygium cumini (Jamun)	Fruit tree	Nectar	April–June	Fruit production and nectar flow	Tropical agroforestry systems	Bradbear (2009); Partap (2011)
Citrus spp.	Fruit tree	Nectar	Spring flowering	High-value honey and fruit production	Tropical and subtropical orchards	Free (1993); Klein et al. (2006)
Litchi chinensis (Litchi)	Fruit tree	Nectar	February–April	Highly pollinator-dependent fruit crop	Subtropical orchards	Partap (2011); Abrol (2012)
Psidium guajava (Guava)	Fruit tree	Nectar and pollen	Seasonal flowering	Fruit production and bee forage	Tropical and subtropical regions	FAO (2018); Free (1993)
Ziziphus mauritiana (Ber)	Fruit tree/shrub	Nectar and pollen	October–December	Dryland fruit crop and bee forage	Arid and semi-arid regions	Crane (1990); Abrol (2012)
Carica papaya (Papaya)	Horticultural crop	Nectar and pollen	Nearly year-round	Fruit crop requiring insect visitation	Tropical farming systems	Klein et al. (2006); Partap (2011)
Cocos nucifera (Coconut)	Plantation crop	Pollen and nectar	Year-round flowering	Oilseed and plantation crop	Coastal tropical regions	Free (1993); FAO (2021)
Areca catechu (Arecanut)	Plantation crop	Pollen	Seasonal	Plantation economy and pollinator support	Humid tropical ecosystems	Partap (2011); FAO (2018)

Species	Category	Major bee resource	Flowering season	Major ecological/ economic importance	Suitable ecosystem/region	Key references
Coffea arabica / *C. canephora*	Beverage crop	Nectar	Seasonal mass flowering	Pollinator-dependent beverage crop	Coffee agroforestry systems	Klein et al. (2006); Schroth et al. (2004)
Camellia sinensis (Tea)	Plantation shrub	Nectar and pollen	Seasonal	Beverage crop and pollinator support	Humid subtropical regions	Free (1993); Partap (2011)
Rosa indica (Rose)	Ornamental shrub	Nectar and pollen	Multiple flowering periods	Ornamental and pollinator-supporting shrub	Gardens and agroforestry borders	Abrol (2012); FAO (2021)
Hibiscus rosa-sinensis	Ornamental shrub	Nectar	Year-round flowering	Ornamental and bee forage shrub	Tropical home gardens	Partap (2011); FAO (2021)
Bougainvillea spectabilis	Ornamental shrub	Nectar	Extended flowering	Hedgerow and ornamental support	Dry tropical landscapes	Abrol (2012); FAO (2018)
Lawsonia inermis (Henna)	Shrub	Nectar and pollen	Summer flowering	Medicinal and dryland shrub	Semi-arid ecosystems	Crane (1990); Abrol (2012)
Vitex negundo	Medicinal shrub	Nectar	Seasonal	Medicinal shrub and pollinator support	Tropical wastelands and field borders	FAO (2018); Partap (2011)

Table 3. Potential vegetable, pulse, oilseed and cereal crops suitable for profitable apisilviculture

Crop	Category	Major bee reward	Pollination dependency	Flowering period	Importance in apisilviculture	Key references
Mustard (*Brassica juncea*)	Oilseed crop	Nectar and pollen	Highly pollinator responsive	Winter	Major honey crop and oilseed	Free (1993); Abrol (2012)
Sunflower (*Helianthus annuus*)	Oilseed crop	Nectar and pollen	Highly pollinator dependent	Spring/ Summer	Enhances seed set and oil content	Klein et al. (2006); Partap (2011)
Sesame (*Sesamum indicum*)	Oilseed crop	Nectar	Moderate pollinator dependence	Summer	Important nectar source in drylands	Crane (1990); Abrol (2012)
Niger (*Guizotia abyssinica*)	Oilseed crop	Nectar and pollen	Pollinator responsive	Winter	Excellent bee forage crop	Free (1993); FAO (2018)
Coriander (*Coriandrum sativum*)	Spice/oilseed crop	Nectar and pollen	Highly insect pollinated	Winter	Aromatic honey and seed yield improvement	Abrol (2012); Partap (2011)
Pigeon pea (*Cajanus cajan*)	Pulse crop	Nectar and pollen	Partially pollinator dependent	Kharif	Improves bee forage continuity and nitrogen fixation	Nair (1993); Free (1993)

Crop	**Category**	**Major bee reward**	**Pollination dependency**	**Flowering period**	**Importance in apisilviculture**	**Key references**
Green gram (*Vigna radiata*)	Pulse crop	Nectar and pollen	Pollinator responsive	Summer/ Kharif	Supports bees and improves soil fertility	Klein et al. (2006); Abrol (2012)
Black gram (*Vigna mungo*)	Pulse crop	Nectar and pollen	Moderate pollinator dependence	Kharif	Bee forage and nitrogen fixation	Nair (1993); FAO (2021)
Cowpea (*Vigna unguiculata*)	Pulse crop	Nectar and pollen	Pollinator responsive	Summer/ Kharif	Multipurpose forage and pulse crop	Jose (2009); Partap (2011)
Chickpea (*Cicer arietinum*)	Pulse crop	Nectar	Limited insect pollination	Winter	Seasonal forage source	Free (1993); Abrol (2012)
Lentil (*Lens culinaris*)	Pulse crop	Nectar and pollen	Partially insect pollinated	Winter	Supports bee diversity	FAO (2018); Partap (2011)
Cucurbits (*Cucurbita spp.*)	Vegetable crop	Nectar and pollen	Highly pollinator dependent	Summer	Requires bee pollination for fruit set	Klein et al. (2006); Garibaldi et al. (2013)
Cucumber (*Cucumis sativus*)	Vegetable crop	Nectar and pollen	Highly pollinator dependent	Summer	Improves fruit yield and quality	Free (1993); Abrol (2012)
Bitter gourd (*Momordica charantia*)	Vegetable crop	Nectar	Highly insect pollinated	Summer	Major bee-attracting vegetable crop	Partap (2011); FAO (2021)
Brinjal (*Solanum melongena*)	Vegetable crop	Pollen	Buzz pollination responsive	Multiple seasons	Enhances fruit quality and seed set	Klein et al. (2006); Abrol (2012)
Tomato (*Solanum lycopersicum*)	Vegetable crop	Pollen	Buzz pollination responsive	Multiple seasons	Increased fruit yield through pollinator activity	Garibaldi et al. (2013); FAO (2021)
Onion (*Allium cepa*)	Vegetable crop	Nectar	Highly insect pollinated	Winter/ Summer	Important seed production crop	Free (1993); Abrol (2012)
Carrot (*Daucus carota*)	Vegetable crop	Nectar and pollen	Highly insect pollinated	Winter	Seed production and pollinator support	Partap (2011); FAO (2018)
Maize (*Zea mays*)	Cereal crop	Pollen	Wind pollinated	Kharif	Pollen source for bees	Crane (1990); Free (1993)
Sorghum (*Sorghum bicolor*)	Cereal crop	Pollen	Wind pollinated	Kharif	Supplemental pollen resource	Nair (1993); Abrol (2012)
Pearl millet (*Pennisetum glaucum*)	Cereal crop	Pollen	Wind pollinated	Kharif	Dryland pollen source	FAO (2018); Partap (2011)
Buckwheat (*Fagopyrum esculentum*)	Pseudo-cereal	Nectar and pollen	Highly pollinator attractive	Winter	Excellent honey crop	Crane (1990); Free (1993)

Among the various crop categories, oilseed crops emerged as some of the most important bee forage plants. Mustard, sunflower, sesame and niger were reported to produce abundant nectar and pollen and support large honey bee populations during flowering seasons (Free, 1993; Abrol, 2012). Mustard-based cropping systems are particularly important in tropical and subtropical apiculture because they support both commercial honey production and pollination services. Sunflower also exhibited high pollinator dependency, with bee visitation significantly improving seed set, seed weight and oil content (Klein et al., 2006). Niger and sesame serve as valuable forage crops in dryland ecosystems where floral resources are otherwise limited.

Pulse crops were similarly identified as highly suitable components of profitable apisilvicultural systems because of their dual roles in pollinator support and soil fertility improvement. Leguminous crops such as pigeon pea, cowpea, green gram and black gram provide nectar and pollen resources while simultaneously enriching soil nitrogen through biological nitrogen fixation (Nair, 1993). These crops improve floral diversity within agroforestry systems and contribute to sustainable soil management. Pigeon pea, owing to its prolonged flowering duration, is particularly important for maintaining bee forage continuity during periods of limited floral availability.

The review further revealed that cucurbitaceous vegetable crops are among the most pollinator-dependent agricultural crops. Crops such as cucumber, pumpkin, bitter gourd and other cucurbits require insect-mediated pollination for successful fruit set and yield development (Klein et al., 2006; Garibaldi et al., 2013). Honey bees and wild bees are therefore indispensable components of cucurbit-based apisilvicultural systems. Bee pollination significantly enhances fruit quality, size, uniformity and seed development in these crops.

Vegetable crops belonging to Solanaceae such as tomato and brinjal were also found to benefit from pollinator activity, particularly buzz-pollinating bees. Although these crops are often considered self-compatible, pollinator visitation improves pollen transfer, fruit set and overall yield quality (Garibaldi et al., 2013). Onion and carrot, especially when cultivated for seed production, exhibited high dependence on insect pollination and support substantial pollinator visitation during flowering.

Cereal crops generally contribute less nectar than other crop groups because most cereals are wind pollinated. Nevertheless, maize, sorghum and pearl millet provide abundant pollen resources that support honey bee nutrition during periods of nectar scarcity (Crane, 1990). Buckwheat emerged as an exceptionally important pseudo-cereal crop because of its high nectar secretion and attractiveness to pollinators, making it one of the most valuable honey-producing crops in temperate and subtropical ecosystems.

The review further indicated that diversified crop combinations significantly enhance pollinator abundance and ecosystem stability within apisilvicultural systems. Agroforestry landscapes integrating flowering crops with multipurpose trees provide sequential flowering patterns, habitat heterogeneity and improved ecological connectivity (Kennedy et al., 2013). Such systems reduce forage scarcity and strengthen resilience of pollinator populations under changing climatic conditions.

Economically, integration of pollinator-dependent crops substantially increases farm profitability because pollination improves crop yield, fruit quality and market value. Honey production from flowering crops provides additional income, thereby diversifying livelihood opportunities for farmers. Pollination services also contribute indirectly to increased agricultural productivity and food security, often exceeding the direct economic value of honey and other hive products (Garibaldi et al., 2013).

3.5 Apisilviculture as a Profitable Agroforestry System

The review of literature clearly demonstrated that apisilviculture is a highly profitable agroforestry practice capable of generating substantial economic returns while simultaneously enhancing ecological sustainability and ecosystem services (Table 4). The integration of flowering trees, agricultural crops and managed pollinators creates multifunctional production systems in which ecological interactions directly contribute to increased productivity and livelihood security (Jose, 2009; Centeno-Alvarado et al., 2023).

The table revealed that apisilvicultural systems provide multiple direct and indirect economic benefits. Direct income is generated through hive products such as honey, beeswax, pollen, propolis and bee colonies, whereas indirect economic gains arise from improved pollination services leading to enhanced crop yield, fruit quality and seed production (Bradbear, 2009; Garibaldi et al., 2013). Several studies indicated that the economic value of pollination frequently exceeds the direct value of honey production because pollinator activity substantially increases agricultural productivity and market quality of crops (Aizen et al., 2009).

Table 4. Economic and ecological benefits of apisilviculture as a profitable agroforestry practice

Component/System	Major outputs/services	Economic benefits	Important examples	Key references
Tree–bee integration	Honey, beeswax, pollen, propolis	Additional annual income from hive products	Neem, eucalyptus, acacia-based systems	Bradbear (2009); FAO (2021)
Fruit tree-based apisilviculture	Fruits + pollination services	Increased fruit set, quality and market value	Mango, citrus, litchi, guava systems	Klein et al. (2006); Garibaldi et al. (2013)
Oilseed crop-based systems	Seed yield + honey production	Increased oil content and seed productivity	Mustard, sunflower, sesame	Free (1993); Abrol (2012)
Pulse crop-based systems	Grain yield + bee forage	Improved pulse productivity and soil fertility	Pigeon pea, cowpea, green gram	Nair (1993); Jose (2009)
Coffee agroforestry systems	Coffee yield + honey	Enhanced coffee quality and pollination benefits	Coffee + Grevillea systems	Schroth et al. (2004); Klein et al. (2006)
Silvipastoral systems with bee flora	Honey + fodder + fuelwood	Diversified livelihood opportunities	Leucaena, Gliricidia systems	Jose (2009); FAO (2018)
Multipurpose tree-based systems	Timber, fruits, fodder, honey	Long-term economic stability	Albizia, Pongamia, Dalbergia systems	Power (2010); Centeno-Alvarado et al. (2023)
Home garden apisilviculture	Vegetables, fruits, honey	Household nutritional and economic security	Drumstick, papaya, hibiscus systems	Partap (2011); FAO (2021)
Pollinator-mediated crop systems	Enhanced crop pollination	Higher crop yield and quality	Cucurbits, onion, carrot	Garibaldi et al. (2013); Kennedy et al. (2013)
Climate-smart agroforestry systems	Diversified farm outputs	Reduced climatic and market risks	Tree–crop–bee integrated systems	Potts et al. (2016); Jose (2009)
Organic apisilviculture systems	Organic honey and produce	Premium market prices	Organic horticultural systems	Goulson et al. (2015); FAO (2021)
Community-based beekeeping systems	Honey and rural enterprises	Employment generation and women empowerment	Tribal and forest-fringe regions	Bradbear (2009); Potts et al. (2010)

Fruit tree-based apisilvicultural systems emerged as particularly profitable because pollination significantly improves fruit set, fruit size, seed formation and shelf life in crops such as mango, citrus, litchi and guava (Klein et al., 2006). Pollinator-dependent horticultural crops therefore generate dual economic benefits through fruit production and honey yield. Coffee agroforestry systems similarly exhibited high ecological and economic importance because shade trees support pollinator diversity while bee pollination enhances coffee quality and productivity (Schroth et al., 2004).

Oilseed crops such as mustard, sunflower and sesame were identified as major nectar-producing crops supporting commercial honey production. Bee pollination improves seed yield, seed filling and oil content in these crops, thereby increasing farm profitability (Free, 1993; Abrol, 2012). Mustard-based apisilvicultural systems are especially important in tropical agriculture because they simultaneously support pollinator nutrition and commercial apiculture during flowering seasons.

Pulse crop-based systems were found to contribute substantially to both ecological sustainability and farm productivity. Leguminous crops such as pigeon pea, cowpea and green gram improve soil fertility through biological nitrogen fixation while also supplying nectar and pollen resources for pollinators (Nair, 1993). Such systems enhance floral diversity and reduce dependence on synthetic fertilizers, thereby lowering production costs and improving sustainability.

The table further indicated that multipurpose tree-based apisilvicultural systems provide long-term ecological and economic stability. Trees such as *Albizia lebbeck*, *Pongamia pinnata*, *Dalbergia sissoo* and *Leucaena leucocephala* produce timber, fodder, fuelwood and nectar resources while contributing to carbon sequestration, watershed protection and biodiversity conservation (Power, 2010). Diversified tree–crop–bee systems therefore improve resource-use efficiency and resilience against climatic and market uncertainties.

Home garden apisilviculture was identified as an important livelihood-supporting system, especially in tropical rural regions. Integration of vegetables, fruits, medicinal plants and bee flora within household gardens enhances nutritional security, pollinator conservation and supplementary income generation (Partap, 2011). Such systems are particularly beneficial for smallholder farmers and women-led rural enterprises because of their low investment requirements and continuous productivity.

The review also highlighted the ecological significance of pollinator-mediated crop systems. Crops such as cucurbits, onion and carrot exhibit high pollination dependency, and adequate bee visitation substantially improves fruit and seed production (Garibaldi et al., 2013). Pollinator-rich agroforestry systems therefore enhance both crop productivity and ecosystem resilience by supporting diverse pollinator assemblages.

Climate-smart apisilvicultural systems were found to improve resilience against environmental stress through diversified vegetation structure, carbon sequestration, microclimatic regulation and reduced soil erosion (Potts et al., 2016). Flowering trees moderate temperature extremes and improve moisture conservation, thereby supporting both crop growth and pollinator activity under changing climatic conditions.

The review further revealed that organic and low-pesticide apisilvicultural systems improve pollinator health and produce premium-value organic honey and agricultural products (Goulson et al., 2015). Reduced pesticide exposure enhances colony survival, pollinator diversity and ecological stability. Consequently, organic apisilviculture is increasingly gaining importance within sustainable agriculture and ecological restoration programmes.

Community-based apisilvicultural systems also demonstrated significant socio-economic benefits including employment generation, women empowerment and poverty alleviation among tribal and forest-fringe communities (Bradbear, 2009). Beekeeping requires relatively low investment and can therefore function as an accessible livelihood option for marginalized rural populations.

Despite these advantages, several constraints continue to affect profitability of apisilviculture, including habitat fragmentation, pesticide toxicity, floral scarcity during lean periods, diseases and inadequate marketing infrastructure (Potts et al., 2010). Therefore, development of flowering calendars, pollinator-friendly landscape planning and policy support are essential for expanding profitable apisilvicultural systems.

Overall, the review clearly demonstrated that apisilviculture is a multifunctional agroforestry practice capable of simultaneously supporting food production, pollinator conservation, climate resilience and ecosystem restoration while generating substantial economic benefits. Diversified tree–crop–bee systems therefore represent sustainable and climate-smart land-use strategies for future agricultural and forestry development.

3.6 Apisilviculture Enhancing Crop Production

The review of literature clearly demonstrated that apisilviculture significantly enhances crop production through improved pollination services, ecological stability and increased pollinator abundance within agricultural landscapes (Table 5). Integration of flowering trees, shrubs and bee-friendly crops creates favorable habitats for pollinators, thereby improving pollination efficiency and crop productivity across a wide range of agricultural and horticultural systems (Garibaldi et al., 2013; Centeno-Alvarado et al., 2023).

The table revealed that pollinator-dependent crops such as mango, citrus, cucurbits, sunflower, coffee and apple exhibited substantial improvement in fruit set, seed development, yield and market quality under pollinator-rich apisilvicultural systems. Honey bees emerged as the dominant managed pollinators, although wild bees, flies, butterflies and other insects also contributed significantly to pollination services (Klein et al., 2006). Pollinator diversity was found to improve not only crop productivity but also yield stability and resilience under varying environmental conditions (Garibaldi et al., 2013).

Fruit crops showed particularly strong responses to pollinator activity. In mango, citrus and litchi, bee pollination improved fruit retention, fruit size, seed development and overall fruit quality (Abrol, 2012). Pollinator visitation also enhanced market value because better pollination generally results in uniform fruits with improved shelf life and reduced deformities. Similar observations were reported in apple orchards where honey bees and bumble bees significantly increased fruit set and fruit uniformity (Klein et al., 2006).

Oilseed crops such as sunflower, mustard and sesame were identified as highly responsive to bee pollination. Honey bee activity increased seed filling, seed weight and oil content, resulting in substantial enhancement in productivity (Partap, 2011). In sunflower, pollination-mediated improvements of 20–40% in seed yield were frequently reported. Mustard fields additionally functioned as important nectar sources supporting honey production during winter seasons, thereby strengthening the economic profitability of apisilvicultural systems.

Vegetable crops belonging to Cucurbitaceae exhibited very high dependence on insect pollination. Crops such as pumpkin, cucumber and bitter gourd require effective pollen transfer for fruit formation and shape development (Free, 1993). The review indicated that bee visitation substantially increased fruit yield, fruit size and seed production in cucurbits. Similarly, onion and carrot seed production systems demonstrated strong dependence on pollinator activity because adequate bee visitation improves seed set, viability and germination percentage.

Pulse crops including pigeon pea and green gram also benefited from pollinator activity despite being partially self-pollinated. Honey bees improved pod formation, seed set and grain yield while these leguminous crops simultaneously contributed nectar and pollen resources for pollinators (Nair, 1993). Such tree–pulse–bee interactions strengthen both agricultural productivity and ecological sustainability through biological nitrogen fixation and improved floral diversity.

Coffee agroforestry systems emerged as excellent examples of profitable apisilviculture. Shade trees within coffee plantations support rich pollinator communities, and bee pollination significantly improves berry set, bean quality and coffee yield (Ricketts et al., 2004). Such systems illustrate the ecological synergy between agroforestry biodiversity and pollination services. Similar interactions were observed in coconut and plantation crop systems where pollinator activity contributed to improved nut setting and productivity.

The review further demonstrated that diversified apisilvicultural systems enhance pollinator abundance and visitation rates because flowering trees and shrubs provide continuous forage and nesting habitats (Kennedy et al., 2013). Agroforestry landscapes therefore function as ecological reservoirs supporting both managed and wild pollinators. Increased habitat heterogeneity improves pollination stability and reduces ecological risks associated with pollinator decline.

In addition to enhancing crop production, apisilviculture contributes substantially to ecosystem services including biodiversity conservation, carbon sequestration, soil stabilization and climate resilience (Jose, 2009). Pollinator-friendly landscapes improve ecological connectivity and support beneficial insects involved in biological pest control and nutrient cycling. Such systems are therefore ecologically superior to simplified monoculture agriculture.

The review also highlighted the economic significance of pollination services. In many crops, the economic value of pollination substantially exceeds the direct value of honey and hive products (Aizen et al., 2009). Improved crop productivity and quality increase market returns, thereby making apisilviculture a highly profitable agroforestry practice for smallholder farmers and rural communities.

Climate change, habitat fragmentation and pesticide exposure were identified as major threats affecting pollinator-mediated crop production (Potts et al., 2010). However, diversified apisilvicultural systems can buffer such stresses by maintaining continuous floral availability, microclimatic moderation and ecological resilience. Therefore, promotion of pollinator-friendly agroforestry landscapes is increasingly considered essential for sustainable food production and climate-smart agriculture.

3.7 Apisilviculture for Sustainable Food Production

The review of literature clearly demonstrated that apisilviculture plays a significant role in promoting sustainable food production through enhancement of pollination services, diversification of farming systems and strengthening of ecosystem resilience (Table 6). Integration of trees, crops and pollinators within agroforestry landscapes creates multifunctional production systems capable of simultaneously supporting food security, nutritional improvement, biodiversity conservation and livelihood sustainability (Jose, 2009; Centeno-Alvarado et al., 2023).

Pollination services emerged as one of the most important ecological functions contributing to sustainable food production. Honey bees and wild pollinators significantly improve fruit set, seed development, crop quality and yield stability in numerous agricultural and horticultural crops (Garibaldi et al., 2013). Approximately 75% of major global food crops depend partially on animal-mediated pollination, highlighting the enormous importance of pollinators in sustaining food systems (Klein et al., 2006). Pollinator-dependent crops such as fruits, vegetables, oilseeds and nuts contribute substantially to global nutritional security because they provide essential vitamins, proteins, oils and micronutrients required for human health.

The table revealed that tree–crop–bee integrated systems are highly effective in improving sustainable food production because they diversify outputs and reduce dependence on single-crop agriculture. Agroforestry systems integrating fruit trees, pulses, vegetables and flowering species provide continuous food supply while simultaneously supporting pollinator populations (Nair, 1993). Diversified systems are ecologically more stable and resilient than monoculture agriculture because they improve habitat heterogeneity, nutrient cycling and ecological interactions.

Fruit tree-based apisilviculture was found to contribute substantially to nutritional security and economic sustainability. Crops such as mango, citrus, litchi and guava showed considerable improvement in fruit set, fruit quality and market value under pollinator-rich conditions (Abrol, 2012). Pollination enhances seed formation, fruit uniformity and shelf life, thereby increasing both productivity and profitability. Honey production associated with fruit orchards provides additional income opportunities and strengthens farm resilience.

Pulse-based apisilvicultural systems emerged as highly important for sustainable food production because pulses contribute significantly to protein security and soil fertility improvement. Leguminous crops such as pigeon pea, cowpea and green gram provide nectar and pollen resources for bees while simultaneously enriching soil nitrogen through biological nitrogen fixation (Nair, 1993). Such systems reduce dependency on chemical fertilizers and improve ecological sustainability of farming systems.

Oilseed crops including mustard, sunflower and sesame were identified as major components of sustainable apisilviculture because bee pollination substantially improves seed yield, oil content and crop productivity (Free, 1993). These crops additionally support commercial honey production during flowering seasons and therefore contribute simultaneously to food and livelihood security.

Table 5. Influence of apisilviculture on crop production and productivity

Crop	Major pollinators involved	Effect on crop production	Improvement observed	Key references
Mango (*Mangifera indica*)	Honey bees, flies, wild bees	Improved fruit set and fruit retention	Increased fruit yield and quality	Klein et al. (2006); Abrol (2012)
Citrus spp.	Honey bees and wild pollinators	Enhanced fruit set and seed development	Better fruit size and market quality	Free (1993); Garibaldi et al. (2013)
Sunflower (*Helianthus annuus*)	Honey bees	Increased seed filling and oil content	20–40% higher seed yield reported	Partap (2011); Klein et al. (2006)
Mustard (*Brassica juncea*)	Honey bees and hoverflies	Enhanced siliqua formation and seed set	Higher oilseed productivity	Abrol (2012); FAO (2018)
Cucurbits (*Cucurbita spp.*)	Honey bees, solitary bees	Improved fruit formation and shape	Significant increase in fruit yield	Garibaldi et al. (2013); Klein et al. (2006)
Coffee (*Coffea arabica*)	Honey bees and native bees	Improved berry set and bean quality	15–25% increase in productivity	Schroth et al. (2004); Ricketts et al. (2004)
Onion (*Allium cepa*)	Honey bees and flies	Improved seed production	Higher seed yield and viability	Free (1993); Abrol (2012)
Carrot (*Daucus carota*)	Honey bees and wild insects	Improved seed set	Better seed quality and germination	Partap (2011); FAO (2021)
Pigeon pea (*Cajanus cajan*)	Honey bees and wild bees	Increased pod formation	Improved grain yield	Nair (1993); Jose (2009)
Green gram (*Vigna radiata*)	Honey bees	Improved pollination efficiency	Increased pod and seed formation	Abrol (2012); Klein et al. (2006)
Coconut (*Cocos nucifera*)	Honey bees and insects	Improved nut set	Increased copra production	Free (1993); FAO (2021)
Apple (*Malus domestica*)	Honey bees and bumble bees	Enhanced fruit set and uniformity	Improved fruit size and quality	Garibaldi et al. (2013); Klein et al. (2006)
Tomato (*Solanum lycopersicum*)	Bumble bees and wild bees	Improved pollination and fruit development	Increased fruit weight and quality	Greenleaf and Kremen (2006); Garibaldi et al. (2013)
Sesame (*Sesamum indicum*)	Honey bees	Improved seed set and capsule formation	Increased seed yield	Partap (2011); Abrol (2012)
Litchi (*Litchi chinensis*)	Honey bees and flies	Enhanced fruit setting	Improved fruit yield and quality	Klein et al. (2006); Free (1993)

Table 6. Role of apisilviculture in sustainable food production and food security

Component/System	Contribution to sustainable food production	Nutritional/Economic significance	Major examples	Key references
Pollination services by honey bees	Enhanced fruit set, seed set and crop productivity	Increased food availability and farm income	Fruit, vegetable and oilseed crops	Klein et al. (2006); Garibaldi et al. (2013)
Tree–crop–bee integrated systems	Diversified food production	Fruits, pulses, vegetables and honey	Agroforestry landscapes	Jose (2009); Nair (1993)
Fruit tree-based apisilviculture	Increased horticultural productivity	Improved nutrition and market value	Mango, citrus, litchi, guava	Abrol (2012); Partap (2011)
Pulse-based apisilviculture	Improved grain production and soil fertility	Protein security and livelihood support	Cowpea, pigeon pea, green gram	Nair (1993); FAO (2018)
Oilseed crop systems	Improved oilseed productivity	Edible oil and honey production	Mustard, sunflower, sesame	Free (1993); Klein et al. (2006)
Vegetable-based apisilviculture	Improved vegetable yield and quality	Nutritional security and income generation	Cucurbits, onion, carrot	Garibaldi et al. (2013); Abrol (2012)
Coffee and plantation agroforestry	Improved plantation productivity	Export-oriented economic gains	Coffee agroforestry systems	Schroth et al. (2004); Ricketts et al. (2004)
Home garden apisilviculture	Household food and nutritional security	Continuous supply of fruits and vegetables	Papaya, drumstick, banana systems	Partap (2011); FAO (2021)
Multipurpose tree systems	Food, fodder, fuelwood and honey	Diversified livelihood support	Neem, moringa, subabul	Jose (2009); Power (2010)
Organic apisilviculture	Reduced pesticide dependence	Safer food and premium products	Organic horticulture systems	Goulson et al. (2015); FAO (2021)
Climate-resilient apisilviculture	Stable productivity under climate stress	Reduced production risks	Tree-based diversified farming	Potts et al. (2016); Centeno-Alvarado et al. (2023)
Community-based beekeeping systems	Rural food and livelihood security	Income diversification and employment	Tribal and forest-fringe systems	Bradbear (2009); FAO (2018)

Vegetable-based apisilvicultural systems also showed strong positive impacts on sustainable food production. Pollinator-dependent vegetable crops such as cucurbits, onion and carrot require insect-mediated pollination for effective fruit and seed production (Garibaldi et al., 2013). Bee pollination improves fruit quality, size and marketability, thereby enhancing both nutritional and economic benefits for farming communities.

The review further indicated that coffee and plantation agroforestry systems provide excellent examples of sustainable food production through ecological integration. Shade trees within coffee plantations support pollinator diversity and biodiversity conservation while simultaneously improving coffee productivity and quality (Schroth et al., 2004). Such systems illustrate the ecological and economic advantages of integrating pollinator-friendly vegetation within agricultural landscapes.

Home garden apisilviculture emerged as an important strategy for household food and nutritional security, particularly in tropical rural regions. Integration of fruit trees, vegetables, medicinal plants and bee flora within household gardens ensures continuous supply of nutritious food while supporting pollinator populations (Partap, 2011). Such systems are especially valuable for smallholder farmers because they require relatively low investment and provide year-round productivity.

The review also demonstrated that multipurpose tree systems strengthen sustainable food production through ecosystem service enhancement. Trees improve soil fertility, reduce erosion, conserve moisture and support carbon sequestration while simultaneously providing fruits, fodder, fuelwood and nectar resources (Power, 2010). Pollinator-friendly agroforestry systems therefore contribute substantially to climate-smart and sustainable agriculture.

Organic apisilvicultural systems were found to improve pollinator survival and reduce ecological risks associated with pesticide exposure. Reduced pesticide use enhances bee health, pollination efficiency and biodiversity conservation while simultaneously producing safer food and premium-value organic products (Goulson et al., 2015). Such systems are increasingly important for sustainable and environmentally friendly food production.

Climate-resilient apisilvicultural systems also demonstrated greater adaptability under changing climatic conditions. Diversified vegetation structure, continuous flowering patterns and microclimatic moderation improve resilience against drought, temperature extremes and ecological disturbances (Potts et al., 2016). Agroforestry systems therefore function as ecological buffers supporting stable food production under climate variability.

Community-based beekeeping and apisilvicultural systems further contribute to rural food security and livelihood diversification, particularly among tribal and forest-dependent communities (Bradbear, 2009). Honey production and pollination services enhance household income while encouraging conservation-oriented land-use practices.

Despite these advantages, the review identified several constraints affecting sustainable food production through apisilviculture, including habitat fragmentation, pollinator decline, pesticide toxicity, climate change and inadequate policy support (Potts et al., 2010). Therefore, promotion of pollinator-friendly landscapes, flowering calendars, diversified agroforestry systems and sustainable pesticide management is essential for strengthening future food security.

3.8 Apisilviculture for Pollinator Conservation

The review of literature clearly demonstrated that apisilviculture plays a crucial role in pollinator conservation through creation of diversified, flower-rich and ecologically stable landscapes capable of supporting both managed and wild pollinator populations (Table 7). Integration of flowering trees, shrubs, agricultural crops and natural vegetation within agroforestry systems improves habitat availability, forage continuity and ecological connectivity, thereby strengthening pollinator abundance and diversity (Jose, 2009; Centeno-Alvarado et al., 2023).

Table 7. Role of apisilviculture in pollinator conservation and ecosystem stability

Component/System	**Pollinator conservation role**	**Major pollinators supported**	**Ecological significance**	**Important examples**	**Key references**
Flowering tree-based systems	Continuous nectar and pollen supply	Honey bees, wild bees, butterflies	Maintains pollinator populations during lean seasons	Neem, jamun, acacia, eucalyptus	Crane (1990); Bradbear (2009)
Agroforestry landscapes	Habitat heterogeneity and nesting support	Honey bees, solitary bees, hoverflies	Enhances pollinator diversity and connectivity	Tree–crop integrated systems	Jose (2009); Kennedy et al. (2013)
Home garden apisilviculture	Diverse floral resources throughout the year	Honey bees and native pollinators	Conserves local pollinator assemblages	Papaya, drumstick, hibiscus systems	Partap (2011); FAO (2021)
Hedgerows and flowering shrubs	Ecological corridors and shelter	Wild bees, butterflies, flies	Reduces habitat fragmentation	Gliricidia, Calliandra, Vitex	Potts et al. (2010); Dainese et al. (2019)
Coffee agroforestry systems	Shade biodiversity and pollinator refuge	Native bees and honey bees	Conserves tropical pollinator communities	Coffee + shade tree systems	Schroth et al. (2004); Ricketts et al. (2004)
Organic apisilviculture systems	Reduced pesticide exposure	Honey bees and beneficial insects	Improved pollinator survival and health	Organic orchards and farms	Goulson et al. (2015); FAO (2021)
Multipurpose tree plantations	Long-duration flowering and habitat support	Honey bees and wild pollinators	Supports ecosystem resilience	Albizia, Pongamia, Leucaena	Nair (1993); Jose (2009)
Pulse-based apisilviculture	Floral continuity and pollen availability	Honey bees and native bees	Seasonal pollinator nutrition	Cowpea, pigeon pea, green gram	Abrol (2012); FAO (2018)
Pollinator-friendly diversified farming	Reduced ecological stress	Multiple pollinator taxa	Stabilizes pollination services	Mixed agroforestry systems	Garibaldi et al. (2013); Centeno-Alvarado et al. (2023)
Forest-edge apisilviculture	Refuge for wild pollinators	*Apis dorsata*, stingless bees	Conserves forest pollinator diversity	Tropical forest landscapes	Potts et al. (2016); Oldroyd and Nanork (2009)
Riparian and watershed vegetation	Floral and nesting habitats	Bees, butterflies and flies	Enhances ecological connectivity	Riverbank plantations	Power (2010); Dainese et al. (2019)
Climate-resilient tree systems	Microclimatic buffering	Heat-sensitive pollinators	Reduces climate-induced pollinator stress	Tree-based diversified systems	Potts et al. (2016); Centeno-Alvarado et al. (2023)

Table 8. Major ecosystem services enhanced through apisilviculture systems

Ecosystem service	Role of apisilviculture	Ecological significance	Major components involved	Long-term benefits	Key references
Pollination services	Enhanced pollinator abundance and activity	Improved crop productivity and plant reproduction	Honey bees, wild bees, flowering trees and crops	Sustainable food production	Klein et al. (2006); Garibaldi et al. (2013)
Biodiversity conservation	Creation of diversified habitats	Conservation of pollinators and beneficial organisms	Trees, shrubs, intercrops and natural vegetation	Ecosystem stability and resilience	Potts et al. (2010); Dainese et al. (2019)
Carbon sequestration	Biomass accumulation and soil carbon storage	Climate change mitigation	Multipurpose trees and agroforestry systems	Reduced atmospheric CO_2	Jose (2009); Power (2010)
Soil conservation	Reduced erosion and improved soil structure	Enhanced soil fertility and stability	Tree roots, litter and vegetation cover	Sustainable land productivity	Nair (1993); FAO (2018)
Nutrient cycling	Litter decomposition and nitrogen fixation	Improved nutrient availability	Leguminous trees and pulse crops	Reduced fertilizer dependency	Jose (2009); Power (2010)
Microclimatic regulation	Temperature moderation and moisture conservation	Reduced heat and drought stress	Tree canopy and diversified vegetation	Climate resilience	Potts et al. (2016); Centeno-Alvarado et al. (2023)
Watershed protection	Improved infiltration and reduced runoff	Hydrological stability	Riparian vegetation and tree systems	Water conservation and groundwater recharge	Power (2010); FAO (2021)
Habitat connectivity	Ecological corridors for pollinators	Reduced habitat fragmentation	Hedgerows, flowering strips and forests	Improved pollinator movement	Kennedy et al. (2013); Dainese et al. (2019)
Biological pest regulation	Support for beneficial insects	Reduced pest outbreaks	Pollinator-friendly vegetation	Reduced pesticide dependence	Goulson et al. (2015); Jose (2009)
Restoration of degraded lands	Improvement of ecological functioning	Recovery of biodiversity and productivity	Tree–crop–bee integrated systems	Sustainable ecosystem restoration	Schroth et al. (2004); FAO (2018)
Livelihood ecosystem services	Diversified ecosystem-derived products	Rural livelihood improvement	Honey, timber, fruits, fodder and fuelwood	Socio-economic sustainability	Bradbear (2009); FAO (2021)
Climate resilience	Enhanced ecological adaptability	Stability under climatic variability	Diversified agroforestry systems	Long-term sustainability	Potts et al. (2016); Centeno-Alvarado et al. (2023)

The table revealed that flowering tree-based systems constitute one of the most important ecological foundations for pollinator conservation. Trees such as neem, jamun, acacia, eucalyptus, pongamia and albizia provide abundant nectar and pollen resources over extended flowering periods and support pollinator populations during seasons of floral scarcity (Crane, 1990; Bradbear, 2009). Continuous floral availability is particularly important for maintaining colony strength, brood development and survival of both domesticated honey bees and wild pollinator species.

Agroforestry landscapes were found to significantly enhance pollinator diversity because structurally heterogeneous systems provide varied floral resources, nesting habitats and microclimatic conditions required by different pollinator groups (Kennedy et al., 2013). Diverse agroforestry systems support honey bees, solitary bees, bumble bees, hoverflies, butterflies and other beneficial insects more effectively than simplified monoculture agriculture. Habitat heterogeneity also improves ecological connectivity and facilitates movement of pollinators across fragmented landscapes.

Home garden apisilviculture emerged as an important localized conservation strategy, especially in tropical rural regions. Home gardens containing flowering fruit trees, vegetables, medicinal plants and ornamental shrubs provide year-round forage and nesting habitats for native pollinators (Partap, 2011). Such systems function as small-scale biodiversity refugia and contribute significantly to conservation of indigenous pollinator assemblages within human-dominated landscapes.

The review further indicated that hedgerows and flowering shrubs play critical ecological roles in reducing habitat fragmentation and establishing pollinator corridors. Species such as *Gliricidia sepium*, *Calliandra calothyrsus* and *Vitex negundo* provide shelter, nesting sites and continuous floral resources for pollinators (Potts et al., 2010). Ecological corridors improve movement and dispersal of pollinators between habitat patches, thereby strengthening pollination services and ecosystem resilience.

Coffee agroforestry systems were identified as globally important pollinator conservation landscapes because shade trees and structurally complex vegetation support high pollinator diversity (Schroth et al., 2004). Native bees and wild pollinators thrive within shaded coffee systems owing to favorable microclimatic conditions, habitat diversity and continuous flowering resources. Similar ecological benefits are observed in cocoa-, citrus- and coconut-based agroforestry systems.

Organic and low-pesticide apisilvicultural systems demonstrated strong positive impacts on pollinator health and survival. Excessive pesticide use has been identified as one of the major causes of global pollinator decline because pesticides impair bee navigation, foraging behaviour, reproduction and immunity (Goulson et al., 2015). Organic apisilviculture reduces chemical stress and supports healthier pollinator communities while simultaneously enhancing biodiversity conservation and sustainable food production.

Pulse-based apisilvicultural systems also contribute significantly to pollinator conservation because flowering legumes such as pigeon pea, green gram and cowpea provide nectar and pollen during critical forage periods (Abrol, 2012). These crops improve floral diversity and nutritional availability for pollinators while simultaneously enhancing soil fertility through biological nitrogen fixation.

The review further demonstrated that diversified pollinator-friendly farming systems improve stability of pollination services and ecosystem functioning. Garibaldi et al. (2013) observed that wild pollinators substantially enhance crop productivity irrespective of managed honey bee abundance, highlighting the ecological importance of maintaining diverse pollinator communities. Diverse pollinator assemblages also improve resilience against environmental disturbances and climatic fluctuations.

Forest-edge apisilvicultural systems emerged as important refugia for wild pollinators such as *Apis dorsata*, stingless bees and native solitary bees. Tropical forest landscapes containing flowering trees and natural vegetation support high pollinator richness and facilitate conservation of specialized pollinator species (Oldroyd and Nanork, 2009). Such systems are especially important in biodiversity-rich tropical regions where habitat destruction threatens pollinator diversity.

Riparian vegetation and watershed plantations were similarly found to contribute substantially to pollinator conservation by maintaining ecological corridors and nesting habitats. Flowering vegetation along riverbanks and watersheds supports bees, butterflies and flies while simultaneously improving soil conservation and hydrological stability (Power, 2010).

Climate change was identified as a major threat affecting pollinator populations through altered flowering phenology, habitat degradation and temperature stress (Potts et al., 2016). However, diversified tree-based apisilvicultural systems provide microclimatic buffering and continuous forage availability that help mitigate climate-induced stress on pollinators. Trees moderate temperature extremes, improve humidity and reduce ecological vulnerability of pollinator populations under changing climatic conditions.

The review also emphasized that conservation of pollinators is directly linked with sustainable food production, ecosystem stability and biodiversity conservation. Decline of pollinator populations can severely affect agricultural productivity, regeneration of flowering plants and ecological resilience. Therefore, promotion of pollinator-friendly apisilvicultural systems is increasingly recognized as a nature-based strategy for ecological restoration and climate-smart agriculture.

3.9 Apisilviculture for Enhanced Ecosystem Services

The review of literature clearly demonstrated that apisilviculture significantly enhances multiple ecosystem services through integration of pollinator-friendly trees, crops and ecological habitats within agroforestry systems. Apisilvicultural landscapes support provisioning, regulating, supporting and cultural ecosystem services that collectively improve ecological sustainability, agricultural productivity and climate resilience (Power, 2010; Jose, 2009).

Pollination services emerged as the most important ecosystem service enhanced by apisilviculture. Pollinators such as honey bees, solitary bees, butterflies and hoverflies facilitate fertilization, fruit set, seed development and regeneration of flowering plants, thereby supporting both agricultural production and natural ecosystem functioning (Klein et al., 2006). Garibaldi et al. (2013) demonstrated that diverse pollinator communities substantially improve crop productivity and yield stability across different agricultural systems. Pollination services therefore form the ecological foundation of sustainable food production and biodiversity maintenance.

The table further indicated that apisilvicultural systems contribute significantly to biodiversity conservation by creating structurally diverse habitats rich in floral resources, nesting sites and ecological refugia. Agroforestry systems containing flowering trees, shrubs, crops and natural vegetation support diverse pollinator assemblages and beneficial organisms more effectively than simplified monoculture landscapes (Dainese et al., 2019). Pollinator-friendly habitats also enhance ecological resilience by stabilizing species interactions and reducing risks associated with biodiversity loss.

Carbon sequestration emerged as another major ecosystem service provided by apisilvicultural systems. Trees and perennial vegetation accumulate substantial amounts of aboveground and belowground biomass while improving soil organic carbon storage (Jose, 2009). Multipurpose tree species integrated within agroforestry landscapes therefore contribute to climate change mitigation by reducing atmospheric carbon dioxide concentrations. Pollinator-supported vegetation regeneration further enhances long-term carbon storage potential and ecological restoration.

The review also revealed that apisilviculture substantially improves soil conservation and soil fertility. Tree roots stabilize soil structure, reduce erosion and improve infiltration, while litter deposition enhances soil organic matter and microbial activity (Nair, 1993). Nitrogen-fixing tree species and pulse crops integrated within apisilvicultural systems improve nutrient cycling and reduce dependency on synthetic fertilizers. Such ecological processes enhance long-term soil productivity and sustainability of agroecosystems.

Microclimatic regulation was identified as a crucial ecosystem service provided by tree-based apisilvicultural systems. Tree canopies reduce temperature extremes, conserve soil moisture and improve humidity conditions favorable for both crops and pollinators (Potts et al., 2016). Diversified vegetation structures therefore enhance resilience against drought, heat stress and climatic variability. Climate-buffering effects are particularly important for sustaining pollinator populations under rapidly changing environmental conditions.

Watershed protection and hydrological regulation were also significantly enhanced by apisilvicultural landscapes. Trees improve water infiltration, reduce runoff and stabilize riparian ecosystems, thereby contributing to groundwater recharge and watershed conservation (Power, 2010). Vegetation cover additionally minimizes sediment loss and improves water quality in agricultural landscapes.

The review further indicated that habitat connectivity represents a major ecological advantage of apisilviculture. Hedgerows, flowering strips, riparian vegetation and agroforestry corridors facilitate movement of pollinators and other beneficial organisms across fragmented habitats (Kennedy et al., 2013). Improved ecological connectivity enhances pollination services, genetic exchange and biodiversity conservation within agricultural landscapes.

Biological pest regulation was another important ecosystem service associated with apisilviculture. Pollinator-friendly diversified systems support predators, parasitoids and beneficial insects that naturally regulate pest populations, thereby reducing dependency on chemical pesticides (Goulson et al., 2015). Reduced pesticide use additionally improves pollinator survival and ecological health.

The table also demonstrated that apisilviculture contributes significantly to restoration of degraded ecosystems. Tree–crop–bee integrated systems improve vegetation cover, ecological functioning and biodiversity recovery in degraded landscapes (Schroth et al., 2004). Pollinator-mediated regeneration of flowering plants further accelerates ecosystem restoration and improves resilience against environmental degradation.

Livelihood ecosystem services were similarly found to be highly important in apisilvicultural systems. Honey, beeswax, fruits, timber, fodder, fuelwood and medicinal products provide diversified income opportunities for rural communities (Bradbear, 2009). Such ecosystem-derived products strengthen socio-economic sustainability while encouraging conservation-oriented land-use practices.

The review further emphasized that diversified apisilvicultural systems are more climate resilient than monoculture agriculture because ecological diversification improves adaptability and system stability under climatic uncertainty (Centeno-Alvarado et al., 2023). Continuous flowering, habitat diversity and ecosystem buffering collectively reduce ecological vulnerability and enhance long-term sustainability.

Despite these benefits, ecosystem services provided by apisilviculture are increasingly threatened by habitat fragmentation, excessive pesticide use, climate change and declining pollinator populations (Potts et al., 2010). Therefore, promotion of pollinator-friendly agroforestry systems, flowering corridors and sustainable land management practices is essential for maintaining ecosystem functionality and resilience.

4. Conclusion

Apisilviculture has emerged as a promising climate-smart and nature-based agroforestry practice capable of simultaneously supporting sustainable food production, pollinator conservation and enhanced ecosystem services. The review demonstrated that integration of flowering trees, crops and pollinators significantly improves pollination services, crop productivity, biodiversity conservation and ecological resilience. Pollinator-friendly agroforestry systems also contribute to carbon sequestration, soil conservation, nutrient cycling, watershed protection and climate adaptation. Economically, apisilviculture provides diversified livelihood opportunities through production of honey, beeswax, fruits, timber, fodder and intercrop yields, while pollination services substantially enhance agricultural productivity and crop quality. Pictorially it is concluded as Fig. 2.

However, habitat degradation, pesticide use, floral scarcity and climate change continue to threaten pollinator sustainability. Therefore, promotion of integrated tree–crop–bee systems, pollinator-friendly landscapes and sustainable management practices is essential for ensuring long-term food security, ecological stability and climate-resilient rural development worldwide.

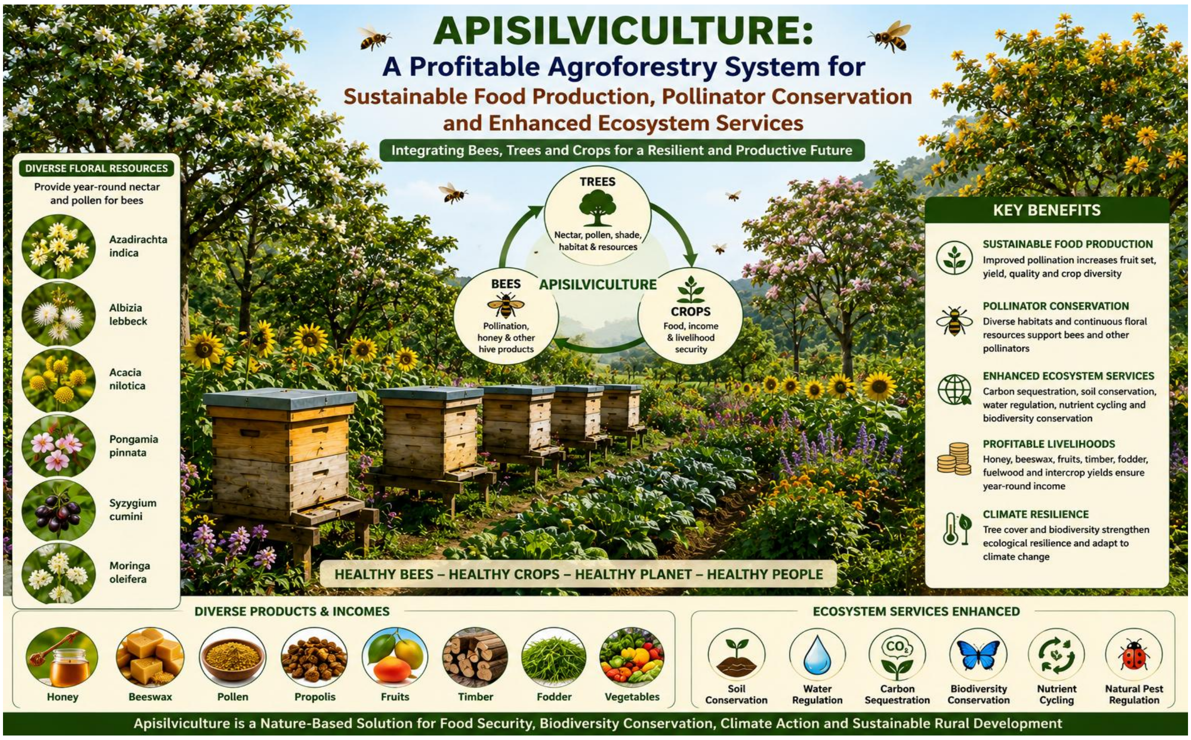

Fig. 2. A pictorial conclusion of Apisilviculture: A profitable agroforestry system for sustainable food production, pollinator conservation and enhanced ecosystem services

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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